High School Students Analyzing the Phenomenology of Superconductivity and Constructing Models of the Meissner Effect

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Abstract

Superconductivity offers many opportunities to explore a relevant phenomenology interesting for students because perceived as a challenge stimulating the construction of models, activating a critical re-analysis of magnetic and electrical properties of materials, bridging science and technology. In the European projects MOSEM1-2, an educational path was developed on superconductivity for high school based on explorative experiments and on-line measurements concerning the Meissner and the pinning effects. Feasibility tests were performed in several Italian high schools with more than 500 students. A research experimentation carried out with 40 selected students, aged 17-19, was focused on the models they develop analyzing the Meissner effect using the field lines representation. Data were collected by the worksheets used by students and by the audio-tape dialogues in the group activities. A qualitative analysis of the students' answers, sentences, explicit reasoning and drawings was performed. The students learning paths show a progressive construction of models based on the ideal diamagnetic properties of superconductors, in which the concept of field has an important role.

Introduction

Several researches stress the need to renew high school physics curricula including contents of contemporary physics (Aubrecht, 1989; Gil & Solbes, 1993; Hake 2000, Ostermann, Moreira 2004). Although, the main attention is oriented to introduce fundamental topics as quantum mechanics and relativity (Ostermann, Moreira 2000a), an increasing number of papers evidences the importance to consider other aspects as superconductivity. Demonstrative experiments of levitation in didactic laboratories were proposed in different setting (Schneider et al, 1991; Abd-Shukor, Lee 1998, Brown 2000; González-Jorge, Domarco 2004; Zwittlinger, 2006; Schorn et al. 2008; Strehlow, Sullivan 2009). Educational paths on superconductivity and papers for teachers, presenting the progress in technical applications of superconductors (Ostermann, et al. 1998a, Gough 1998, AAVV 2007), can activate the construction of models, a critical re-analysis of the knowledge about magnetic and electrical properties of materials, stimulating links between science and technology, bridging classical and quantum physics (Ostermann, Moreira 2004), opening a reflection on NOS (Tasar 2009). Educational paths implemented in high school with students and with teachers in formation constitute first positive feasibility tests (Ostermann 2000, Ostermann, Moreira 2000b, 2004; Schorn 2008; Tasar 2009).

To overcome the descriptive-qualitative approach usually followed in the quoted works, in the context of the European projects MOSEM1-2 (AAVV 2010, 2011; Kedzierska et al. 2010), an educational path on superconductivity in high school was developed and experimented by the Italian partners of the projects coordinated by Marisa Michelini at University of Udine. From researches, performed in several Italian schools with more than 500 students and 100 teachers, emerged a differentiated spectrum of educational paths integrating superconductivity in the ordinary high school curricula, involving students in the analysis of the phenomenology and focusing on the conceptual understanding of the processes at the base of superconductivity levitation (Corni et al. 2009; Michelini, Viola 2011; Viola 2010).

Here a research carried out with a group of selected students from all Italy is presented, with the purpose to give a contribution on two levels: the exploration patterns of students facing Meissner levitation; the models developed by students analyzing this phenomenon having the field lines representation as conceptual references.

Methodologies of the qualitative research (Bliss et al. 1983; Erickson 1998; Savenye, Robinson 2011), the taxonomy of causal model of Perkins & Grotzer (2000) and the Types of Models of Windschitl, Thompson (2004), are at the base of the theoretical framework of the present study, focalizing on the following research questions:

RQ1) What models are activated in students from the analysis of different aspects of the phenomenology and how these models evolve?

RQ2) Which aspects of the levitation students suggest to explore to understand the Meissner effect and what sort of hypothesis they want to verify/falsify? What models are embodied in such cases?

RQ3a) What models are activated in their analysis of the Meissner effect and RQ3b) What are the conceptual references that students use?

RQ4) Which are the most problematic knots?

The context of the research experimentation

The research experimentation here presented was performed in 6 hours with 40 students, subdivided in two groups: GR1 consists of N1 = 24 students of grade 12 (aged 17/18) without previous scholastic formation on electromagnetism; GR2 consists of 16 students of grade 13 (aged 18/19), with a 1-year scholastic formation on electromagnetism. The students, selected from schools from all Italy and attending the Summer School held at University of Udine in July 2011, were involved using tutorials in personal and free explorations of the breakdown of resistivity (2h) and of the Meissner effect (4h), as it will be discuss in the next paragraph. Before the activity concerning superconductivity, the students were involved in a module of 6 hours on magnetic phenomena and electromagnetic induction, constructing operatively the field line representation and the concept of flux.

The step explored by students, the monitoring tools.

The educational path, at the base of the experimentations here documented, implement an IBL approach (Michelini, Viola 2011) using a set of hands-on/minds-on apparatuses designed with simple materials and high technology kits (AAVV2010, 2011, Kedzierska E. et al. 2010), YBCO samples, USB probe to explore resistivity versus temperature of solids (Gervasio, Michelini 2010). In the experimentation here discussed the students were involved in the following explorative steps:

S0) Measurement of the Breakdown of resistivity of an YBCO disc;

S1) Exploration of the magnetic properties of different objects: interaction of a magnet and different objects put on the table, to recognize the ferromagnetic ones; interaction between two free and constrained magnets, interaction of a strong neodimium magnet and paramagnetic and diamagnetic systems suspended on a wire or on a yoke in order to make evident even very small repulsive/attractive forces;

S2) Interaction between a little strong magnet (magnet1) and an YBCO disc at room temperature ($T_{\circ}$)

S3) Analysis of the situation: a sandwich composed by magnete1/YBCO/ferromagnetic ring at T=T° is lifted, pulling the magnet

S4) Levitation of the magnet1 posed on the YBCO disc cooled at the temperature of liquid nitrogen (T_{NL})

S5) Analysis of the stability of the levitation

S6) Students design and perform free experiments to explore the phenomenology

S7) Re-analysis of the Meissner Levitation and comparison with other magnetic suspensions

S8) Drawing the field lines for magnet1 and YBCO at T=TNL

S9) Analysis of the situation S3 at T=TNL

S10) Levitation of the magnet1 posed on the YBCO at T° and then cooled at T_{NL}.

S11) Students synthetize the main characteristic of the Meissner effect

These steps where systematically monitored, using five tutorial worksheets (WS0, WS1-4), audio recording of the student dialogues, notes registered by the researchers conducting the interaction with students. The strategy adopted includes the following phases: presentation of a situation-problem, experimental exploration of it, student individual answer to the questions of the related worksheet, discussion in little group on single questions, discussion in large group at the end of each worksheet.

Data was collected prevalently by the two worksheets used during the initial and final phases of the analysis of the Meissner effect levitation: worksheet-0 (fig 1) and worksheet-4 (fig 2). Qualitative data where supported by the audio taped dialogues of the students during the activity.

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Mettersi in gioco nell'esplorare e interpretare fenomeni di superconduttività

Nome e Cognome…………………………………………….. GR ………… Udine ……….

Worksheet 0. Preliminary exploration of the interaction of a magnet and an YBCO disc

An initial exploration of the interaction of a disc of YBCO ($Y\,Ba_2\,Cu_3\,O_{7-\delta}$) with a magnet is proposed, first at room temperature To and then at liquid nitrogen temperature T_{NL}.
A. For each situation Describe the results of the interaction and the conclusion that can be drawn

Situation	Results of the interaction	Conclusion
A1. A magnet is moved closer to an YBCO at T=T°		
A2. An YBCO disk at T=T° is over a ferromagnetic ring. A magnet is over the YBCO. The magnet is lifted.		
A3. YBCO at T=TNL and the magnet moved closer over it		
A4. YBCO at T = T_{NL} and magnet levitating, shifted slightly from the equilibrium position		

The point A of the worksheet-0 suggests a preliminary analysis of four situations (S2-S5 and fig. 1), asking "outcome of the interaction and relative conclusion".

Point B on the worksheet-0 requires students to "Design situations and trials to be conducted to explore the phenomenon of levitation, report them on the table with the hypothesis underlying each (What hypothesis do you want verify?)" (S6).

Figure 2 shows the points A-C-F-G, concerning the analysis here documented.

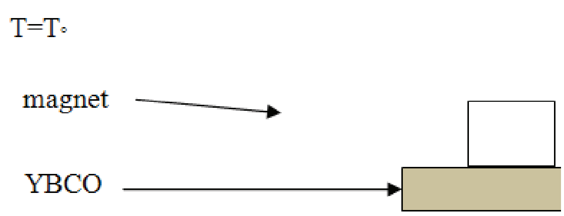
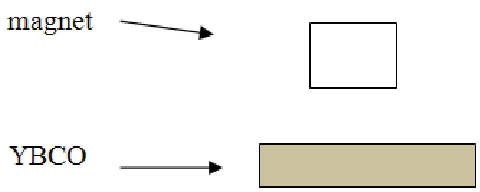
<table>
<tr><td>Point A) A magnet is moved closer to a disc of YBCO at room temperature T° by placing it on top of the magnet, as shown in Figure
A1. Draw the field lines for the system represented in figure</td><td colspan="2"></td></tr>
<tr><td colspan="3">Point C. Draw the resulting magnetic field lines when the temperature is T = YBCO Explain the drawing done.</td></tr>
<tr><td colspan="2">Drawing (T=TNL)
</td><td>Explanation</td></tr>
<tr><td colspan="3">Point F. conclusions that can be drawn from the observation that the magnet cann iron ring and the YBCO, when it is at T = TNL</td></tr>
<tr><td colspan="3">Point G. The observed effect is called the Meissner Effect, It characte superconductor in a peculiar way together with the annulment of the electrical r when the temperature becomes lower than a critical temperature Tc, the temper phase transition (see experiment carried out in Lab).
Based on the observations done which aspects characterize the Meissner effect?</td></tr>
</table>

Figure 2. Points A, C, F, G of the worksheet-4, in which students are request to use the field lines to describe the levitation Meissner effect and then summarize the aspects that characterize it.

In the points A and C students are required to draw the field lines in the configuration shown respectively at T° and T_{NL} (S8). The last two points aims at collecting how students characterize the Meissner effect in a specific phenomenology (point F -S9) and in the final summary (point G -S11).

Data analysis methodology

A qualitative analysis (Erickson 1998) of the student's answers, sentences and drawings was performed, for what concern the following points:

A. Worksheet-0-first part – descriptive models or models with interpretative elements, local and partial models, and global type models, bringing together concepts and processes, providing causal connections (Nersessian 1987);

B. Worksheet-0-second part - models developed with descriptive or interpretative elements of a local and partial, or global and, bringing together concepts and processes, provide causal connections;

C. aspects of the phenomenology that students consider relevant to understand the phenomenon of levitation, focus of exploration proposals and whether they are only procedural or seek to verify/falsify hypotheses;

D. Worksheet-4-Points A/C. Representation of the magnetic field outside and inside the superconductor, at T=T° and at $T=T_{NL}$ and type of representation of the B=0 condition

E. Way in which the Meissner effect is described at the end of the experimentation, aspects on which students focus on (points F/G worksheet-4).

According to the taxonomy of causal model of Perkins & Grotzer (2000) and the Types of Models of Thompson, Windschitl M (2004), the conceptual constructs of student were classified in the following categories: *Developmental models* represent the changes over time, or evolution of an object or of phenomena; *Classification models* depict relationships among different types of objects; *Underlying Causality models* evoke causal connections without specifying them; *Relational Causal models* provide single connections of cause-effect, partial and local*; Emergent Causality models* include chains of causal relations triggered by global visions of phenomena.

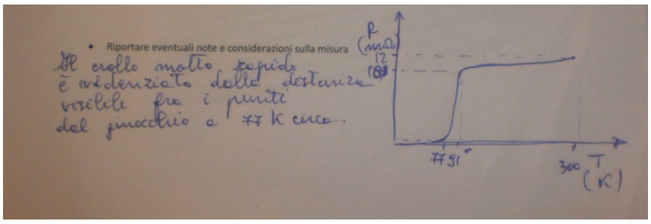
The frequencies of the categories emerged were evaluated, performing a χ^2 test to evidence differences with ages in the distributions.

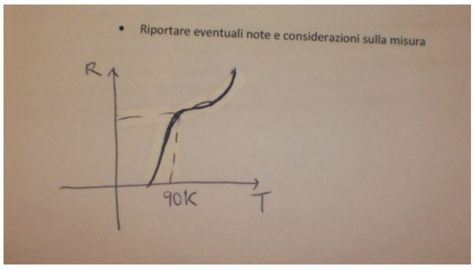
Data analysis and findings

The experimental analysis of the breakdown of the resistivity

In the initial experimental analysis of the breakdown of the resistivity of a disc of YBCO, the students evidence in their graphs (Fig. 3), only the start/end temperature of the process (13/40), both of these (27/40), also the initial value of the YBCO resistance (20/27).

Captions, completing 19/40 graphics, emphasize the "rapidity" of the breakdown or the short range of temperatures in which it occurs. Only in three cases they provide an interpretation, documenting previous readings on the subject ("at low temperatures to explain the phenomenon at microscopic level there is a theory called BCS, according to which the electrons arrange themselves to form pairs, called Cooper pairs, that do not exchange energy with the lattice")





The analysis of the graph R-T acquired in real time has activated in all students (40/40) developmental models based on the crucial role of the temperature of YBCO sample. In the majority of cases (27/40), it activated also the recognition that the phenomenon analyzed consists in a sudden change of YBCO properties (27/40). The need for an interpretation of the process remains at an implicit level at this stage, a part for the few students having prior knowledge.

The initial exploration of the Meissner effect

Worksheet0: Situation A1) **–** As for what concerns the magnet moved closer to an YBCO at T=T° and the observation that does not occur any interaction or at least any apparent (38/40), or a slight attraction (2/40), the students' conclusions have two disjoint categories classification models, focusing on: the possible magnetic properties of YBCO (MA1-29/40) ("it is not ferromagnetic" - 21/29, "has no magnetic properties" - 4/29, "has paramagnetic properties" 2/29), the ontology of YBCO (MB1 10/40 - "is not a magnet" or "a ferromagnet"). The disjunction between ontology of the system and its properties, also confirmed by the analysis of students' dialogues, shows that for them there is no implication between the two. In one case the idea emerges (MC1): "there is no electric stimulus between the two materials", well known identification of electric and magnetic phenomena (Borges, Gilbert 1996).

Worksheet-0: Situation A2) – With regard to the situation in which a magnet lifting the sandwich magnet/YBCO/ring at T = T °, the models categories emerged are summarized in Fig. 4.

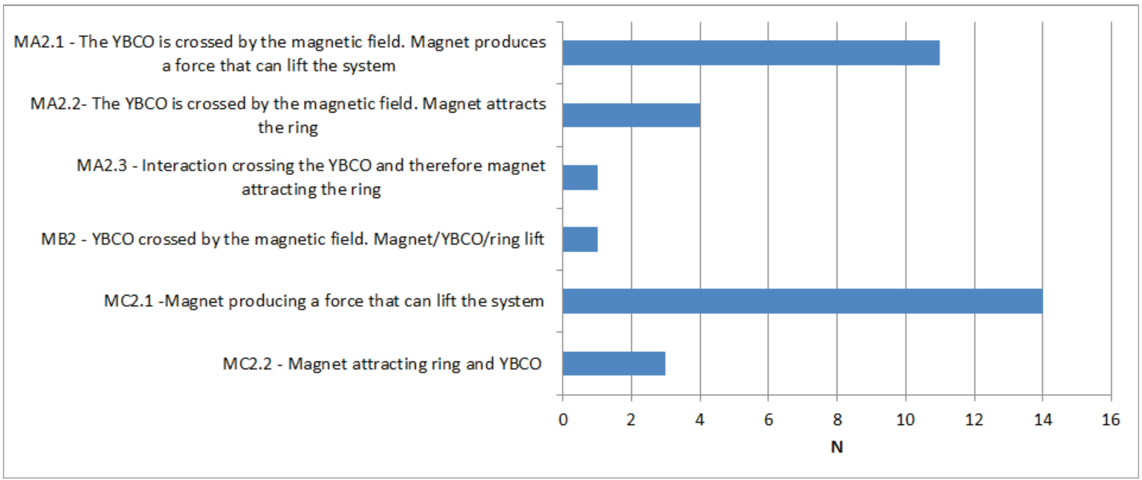


Figure 4. Model categories, highlighted in the explanations of the point S3

In the categories MA2.1-3, including slightly more than half of the sample (21/40), the Emergent Causality models have two fundamental aspects to account for the phenomenon: an entity crossing the YBCO, the magnetic field (categories MA2.1 -MA2.2), the interaction (category MA2.3); the attractive interaction between magnet-ring.

The Relational Causality model of Category B includes only the first aspect, being implicit the interaction. The finding that an entity must cross the YBCO in order to observe an effective magnet-ring interaction, common to the 23/40 response of the categories MA2 and MB2, was activated by the exploration of the interaction between a magnet and a ferromagnetic object through a paper or a wooden surface of a table (S1), as emerged in the motivations expressed by the students dialogues.

The Underlying Causality models of categories MC2.1 and MC2.2 remain on the phenomenological description of the interaction of attractive type, made explicit in terms of forces only in MC2.1.There is no correlation between the types of responses and the age of the students, or their previous formation level ($\chi^2(6)=6,4$, $p<0,01$). In line with the Galili's research (1995), only in 5 cases the recognition of reciprocity in the magnet-ring interaction and the analysis of the forces acting is still partial.

Worksheet0: Situation: A3) – In the first observation of the phenomenon of levitation of a magnet above an YBCO disc, previously cooled at T = TNL, five macrotypes of models, can be recognized:

- MA3. Emergent Causality models, in which starting from the observation of the phenomenon, the direction of magnet-YBCO interaction at T <TNL is recognized (13/40), the YBCO behavior is characterized (4/13, who has used expressions in point A1) or a property is attributed to the YBCO (9/12, who characterized with a property in the YBCO at T °), acquiring “diamagnetic properties” or “diamegnetic behavior” (6/13), evidencing unspecified magnetic properties (3/13), showing “ferromagnetic behavior” (1/13), the “properties of a magnet” (3/13).
- MB3. Emergent Causality models, in which the magnet levitates because the YBCO generates a magnetic field (4/40)
- MC3. Related Causality models based on the force concept (15/40) and in particular, on:
- equilibrium of two forces (8/40): “There is a strong repulsion, but also attraction between the two bodies”, “There is an equilibrium between the gravitational force and a repulsive force”; the effect of a single force, repulsive (9/40) or attractive (1/40)
- MD3. Related Causality model based on the idea that “The magnet levitates above the steam generated from liquid nitrogen” (2/40).

Two students, finally, simply noted that “magnet is inclined not endorsed on the YBCO” and that “The magnet levitates on YBCO at TNL for the Meissner effect.”

In the category MA3 and in almost all of the answers of the category MB3, on the basis for the choice of the magnetic properties to the YBCO there is an analogical reasoning aimed at giving account only to the repulsion, for those attributes diamagnetic properties to YBCO, only to the intensity of interaction observed, for those assigning to the YBCO or ferromagnetic properties or the property of a magnet.

In the category MC3 we can recognize three different models based on the concept of force: the balance of the Meissner repulsion and attraction due to the residual pinning, the equilibrium between weight and repulsion force, a single interaction force between the magnet and YBCO, which makes account of levitation, in which it is clear the partial analysis of the forces acting already underlined.

The category MD3), definitely in the minority and disappeared in the later stages underlying the knot of recognition that the interaction YBCO-magnet have magnetic nature, emerged in the proposed exploration of other students.

Worksheet-0: A4 – As regards the situation in which the magnet levitate on the YBCO at T = TNL is moved slightly from the equilibrium position, in the table 1 are summarized models of students.

Table 1. Model used in the description of the first exploration of the stability of levitation

MA4- Behavior	Magnet "keeps the inclined position, the magnet levitating until the YBCO is at T = TNL or falls"	5
MB4.1-Equilibrium	Magnet "oscillates, returns to the equilibrium position"	15
MB4.2-Equilibrium of forces	"The magnet returns to the equilibrium position, forces are balanced and the magnet remains inclined"	4
MB4.3 Equilibrium: Minimum of potential energy	“If the displacement is slight, it back to equilibrium position otherwise if it is greater, it falls out. If the magnet is in levitation, it is in a state of equilibrium and of the lower level of potential energy”	3
MC4 Two magnet	The magnet “returns to its equilibrium position. It is realized the case ‘interaction between two magnets’ "	5
MD4 Diamagnetism	“The magnet back to its equilibrium position. The diamagnetism of YBCO makes remain the magnet in equilibrium”	2
ME4 Magnetic field	“The magnet tends to return to equilibrium. The magnetic field does not allow the leak of the magnet from the field of the YBCO”	5
MF4 Electric current	“The magnet remains in the equilibrium position. The YBCO has this behavior below a certain temperature. A current is probably generated, which hinders the movement of the magnet”	1

With the exception of the Developmental models of minority category MA4, in almost the entire sample, the concept of equilibrium is included starting from the description of the phenomenon, resulting the central concept of the Relational Causality models of the category MB4. In the remaining categories, including 13/40 students and Emergent Causality models, the phenomenon is caused by the interaction between two magnets (cat. MC4), the diamagnetism YBCO (cat MD4), the magnetic field created by the presence of YBCO (cat. ME4), the current developed inside the YBCO (cat. MF4). At this stage, the students, with no significant differences between the two groups ($\chi^2(8)=6{,}5$, $p<0{,}001$), analyze levitation mainly as a static interaction between the magnet and YBCO, providing only the dynamic aspects of the last two categories.

Worksheet-0- Point B - Experimental design

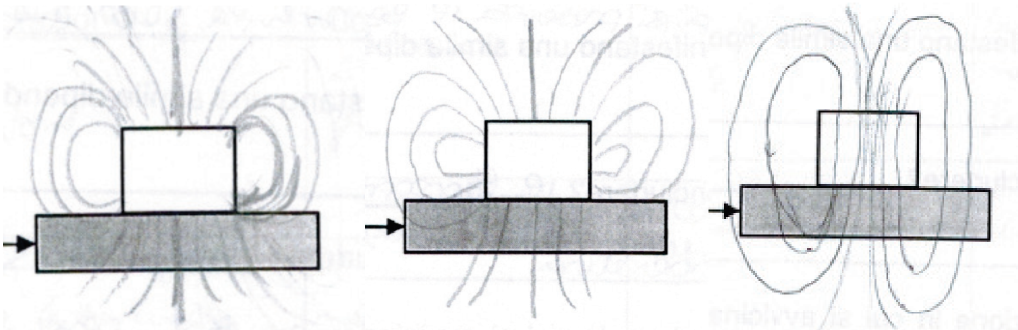
When asked to design experiments to understand the phenomenon of levitation, the students proposed on average 2.0±1.1 (max 5) different contexts, and 2.3 ± 1.1 (max 5) actually different experiments.

Next to several proposals for behavior exploration (2/3 “try to see what happens if ...”), a significant part (one third) of the experiments is aimed at verifying/falsifying interpretative hypotheses covering the following full range of contexts (categories not exclusive), all significant for the characterization of the phenomenon: role of T (18/40); properties YBCO (16/40); characteristics of the interaction YBCO-Magnet and in particular its magnetic nature (27/40) ; measurement of the parameters which determine the interaction (26/40); interaction of a YBCO with objects of materials with different magnetic properties (19/40); behavior / electrical properties YBCO (9/40)

Half of the sample adopts a verify approach, proposing to change the geometry or the properties of the systems involved. The remaining half aims at falsifying hypothesis, proposing to explore if the levitation occurs or not by changing a specific condition (e.g. “The magnetic field of the SC is similar to that of a magnet. Observation. If there is a magnetic field, the magnet would turn and would manifest attraction “). There is no dependency between age and approaches ($p < 0.1$). Such an attitude, not common among students (Park et al 2001), is particularly important here as it has led to design situations that highlight the dynamic nature of the processes underlying the phenomenon.

The analysis of the effect Meissner at the end of the path

Worksheet-4 –Point A. All the representations of the magnetic field at T = T ° include lines which radiate from the poles of the magnet, through the superconductor, are open close to the magnetic axe. They differ in the three types shown in Fig. 5, in which emerge the main difference between the groups GR1 and GR2, regarding how they drawn the magnetic field lines: also depicted inside the magnet, which protrude only from the bases of the magnet, frequent drawing, also present in the textbooks (Tipler 1991, Haber-Scaim U, et al. 1995) (4/40 all of GR2); represented only on the outside of the magnet, which protrude from the base areas (28/40, 15 of GR1 and GR2 13); external to the superconductor and protrude from both bases from both side surfaces of the magnet (8/40, all of GR1), as recognized in the exploration of the camp with compasses

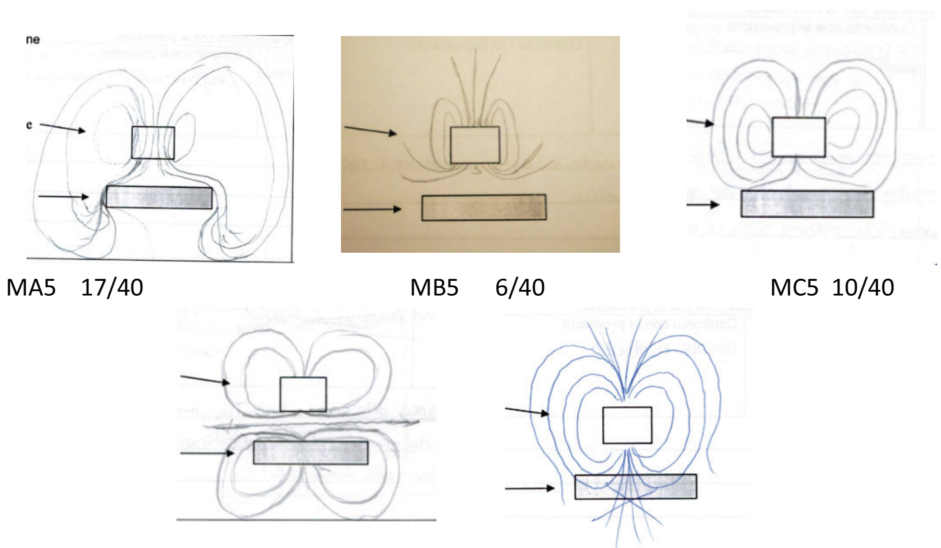


R1) 4/40 R2) 28/40 R3) 8/40

Figure 5. Representations of the field of the magnet at T=T°

Worksheet-4 –Point C. In 38/40 representations of the magnetic field when the superconductor is at T = T_{NL} the following 5 types can be recognized (Fig. 6): MA5) the field lines are present inside the magnet, are deformed in the vicinity of the superconducting winding it externally; MB5) All field lines are external to the magnet and curved upwards; MC5) the field lines are shifted almost rigidly upward and are external to the magnet and the YBCO; MD5) the field lines are produced both by the magnet and by the superconductor; ME5) the field produced by the magnet is external to it and with it rigidly raised, penetrating inside the superconductor. These representations are in agreement with those obtained in previous studies (Viola 2010).

Analyzed in horizontal lines, 33/40 representations of Fig. 6 include the condition B = 0 in the SC, peculiar of the Meissner effect. Only for 5 students the magnetic field crosses the YBCO. The same representations analyzed in vertical lines indicate that for 26/40 (categories MA5-MB5-MD5) the interpretative key lies in the deformation of the magnetic field produced by the magnet. The remaining representations (12/40, MC5-ME5 categories) evidence the model for which the magnetic field is only shifted and rises with the magnet, not being changed by the superconductor. When prompted to indicate the cause of the lifting magnet, these students have referred to a “repulsion between …..like magnets, but it is not like that…” The recognition that the interaction is different from that of the interaction between magnets is not followed by the construction of an alternative model.



MA5 17/40 MB5 6/40 MC5 10/40

MD5 3/40 ME5 2/40

Fig 6. Representation of the field at T=T_{NL}

Worksheet4 –Point F. The sandwich magnet/YBCO/disc at T=TNL. Figure 7 shows the types of conclusions about the negative outcome of the attempt to raise the YBCO with a magnet placed above a ferromagnetic ring at T = TNL. About one-third have been activated Emergent Causality models centered on the absence of magnetic field inside the superconductor (27/40 of the categories MA6-MB6-MC6). In such models it is also made clear that there is an effective interaction between the magnet and the ferromagnetic ring (9/27) and/or that the process is observed when the YBCO is in a superconducting state (7/27). In the category MD6 the phenomenon is described with Relational models based on the change in the magnetic properties YBCO (“it becomes diamagnetic”). A minority describes the phenomenon with Developmental models (cat MD6) or evades the question (NA).

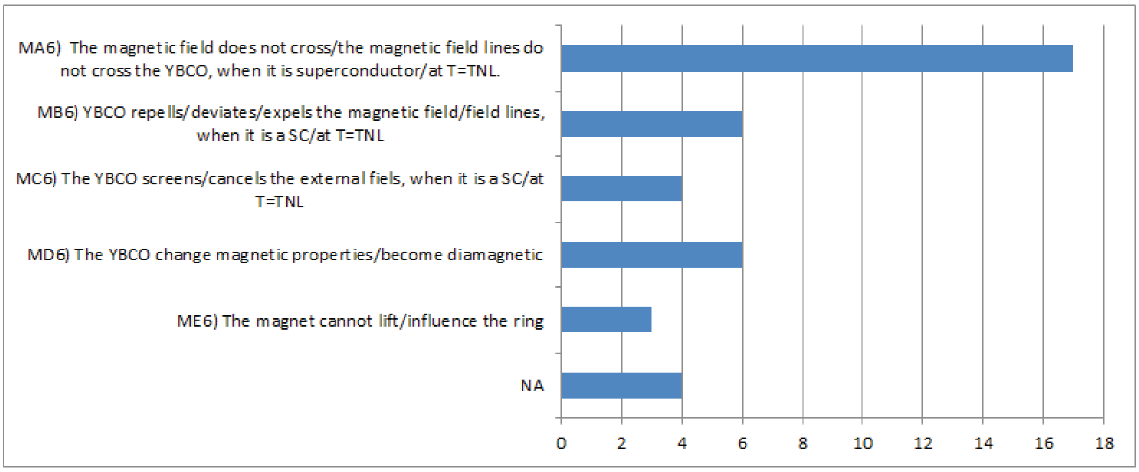


Figure 7. Frequency distribution of the models embedded in the description of punt S9

Worksheet-4 –Point G. Characterization of the Meissner effect

In the following are reported the categories in which the Meissner effect was synthesized, leading to Fig. 8, the distribution of the related frequencies:

MA7) existence of a critical temperature Tc and/or repulsion/levitation (“The SC below a certain T repels the magnet, thus making it levitate”)

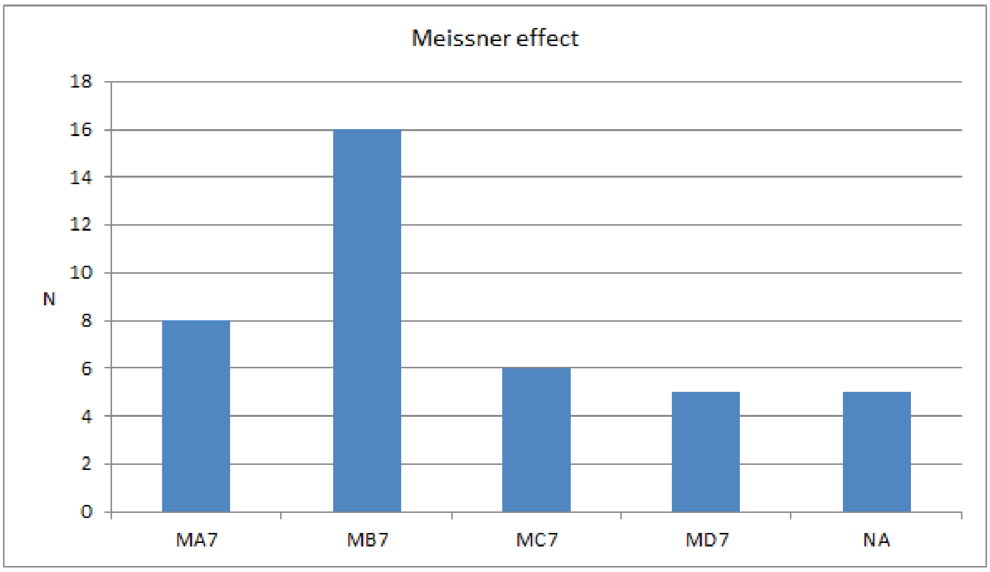
MB7) diamagnetism of YBCO, in more than half of cases also Tc (“The Meissner effect provides that an SC, brought below a TC, changes its magnetic properties, becoming a diamagnet presenting therefore the capability to repel the magnets”, the field lines “do not cross”, “are repulsed outside” the Superconductor, “YBCO screens the magnetic properties”).

MC7) R=0, in half of cases also Tc (“it is an effect that occurs only below TC and is closely connected to the annulment of the electrical resistance”)

MD7) B=0 and R=0; “The expulsion of the magnetic field related to a fast annulment of the resistance”.

The Meissner effect occurring only below a critical temperature is the phenomenological aspect emerged predominantly in the responses of students (23/40), as the only aspect in the category MA7. This effect is characterized indicating that the YBCO becomes a perfect diamagnet or that the magnetic field vanishes inside (21/40 cat MB7 and MD7). A minority characterizes the Meissner effect with the cancellation of the YBCO resistance (11/40 cat MC7-MD7), being a few students who have related electrical and magnetic properties of the superconductor (5/40 cat MD7).

In 15/27 of cases the concept of magnetic field is the basis of the answers from section F to section G.



Conclusions

In the perspective of including modern physics in school curricula, superconductivity is a privileged area both for its relevant technological applications and for the different levels of its interpretation. In the context of European projects MOSEM1-2, a teaching proposal was developed on superconductivity integrated into the high school curricula of electromagnetism, focused on the exploration of the phenomenological magnetic and electric properties of superconductors.

Research experimentations have been carried out in several Italian schools and formed the basis for the research documented here, carried out with 40 students of two different age groups (17-18 and 18-19 years old) selected from schools from all Italy.

Activities with students were monitored with tutorial worksheets, making a qualitative analysis of students' sentences and drawings in the first exploration phase of the Meissner effect and at the end of a 6-hour course. Conceptual constructs of students were classified according to the causal model taxonomy of Perkins & Grotzer (2000) and the Types of Models of Thompson, Windschitl M (2004). These data were integrated with those emerged from the audio recordings of the small and large groups phases.

The main models emerged from students' responses are centered on the concept of the magnetic field and the magnetic properties of the systems involved (RQ3a), highlighting interesting patterns (RQ1).

In the initial analysis of the levitation of a magnet on a superconductor cooled to T=TNL, were identified two main groups of models (RQ1): a first group of Emergent Causality models is based on the magnetic properties or behavior of YBCO in the presence of a magnet, or on the resulting magnetic field created by the presence of YBCO under the magnet; a second group of Relational Causal Models is based on the concepts of force and balance. The static vision underlying these models (RQ1) was modified by some students as early as the preliminary design of the proposed exploration of the phenomenon. These proposals ranged on areas, relevant to characterize the Meissner effect, in which prevail: the analysis of the role of temperature in the process, triggered by the initial experimental exploration of the breakdown of resistivity; the study of how a superconductor interacts with other objects made of different materials, aimed at recognizing its electrical and magnetic properties; the phenomenological parameters of the identified interactions. In more than half of the sample these proposals were intended to falsify and not to verify hypotheses, what is so unusual (Park et al 2001) and rich in implications for the learning process (RQ2).

In the analysis of the levitation magnet on the YBCO, at the end of the path exploration, the majority (5/6) represented the condition B=0 inside the superconductor with three different models: the resulting field that surrounds the YBCO; the upward deformation of the field lines produced by the magnet; the translation of the field rigidly to that of the magnet (RQ3). In the first two types, which have been classified as Emergent Causality models, the levitation is the result of the configuration of the magnetic field created by the YBCO presence. The analog models underlying these representations have a global conception because they include a chain of causal connections, the synthesis of different explored situations, each of which alone does not explain the different aspects of levitation: the field configuration of two magnets maintained with poles counterparts facing; the repulsion between magnets and diamagnetic materials associated with a small reduction of the magnetic flux in the material; the strong deformation of the field lines in presence of a ferromagnetic object (RQ3b). In these models remain open what are the forces developed and the conditions under which they originated (RQ4), highlighting difficulties in the integration of mechanical concepts in electromagnetism (Galili 1998).

The Relational Causal model, on which the third type of students' representation is based, adopted also in a few representations in which the field penetrates the YBCO, subtends two aspects: the conception that the magnetic field produced by the magnet is present in a limited region of space, is static and rigidly associated to it (Borges, Gilbert 1998); the idea that the YBCO acts directly on the magnet, not by modifying the configuration of the magnetic field (RQb3). In this case, the recognition, that the interaction magnet-YBCO is different from the interaction between two magnets, is not followed by the structuring of an alternative interpretative model (RQ4).

A fourth emerged relational causality model foresees that the YBCO produces a magnetic image field of that of the magnet. This model is spontaneously activated by the observation of the magnetic levitation phenomenon (RQ1a) and it recalls the model of image field used in literature to discuss the stability of levitation (Arkadiev 1947). It has remained a strong conceptual reference, for those focused on the stability of levitation, and it emerged in the answers of almost half of the sample in the different steps of the path, being expressed in a direct way like "the situation of repulsion between two magnets is realized", in terms of behavior "acting like two magnets that repulse each other", as a hypothesis to explore "verify whether TLN YBCO is a magnet" (RQ3). This model impedes the understanding of the dynamic nature of the "image field" produced by the fundamental electromagnetic induction, in order to understand the nature of the Meissner effect (Badía-Majos 2006). The synthesis models discussed above contain elements to overcome such a limit (RQ4).

The significance of the recognition that B = 0 is supported in the present work also by the fact that a large part of the sample (over 2/3) based (1) the analysis of the interaction between a magnet and a ferromagnetic ring with the interposed disc of YBCO, and (2) the characterization of the Meissner effect at the end of the path, on the cancellation of the field inside the superconductor or on its nature of perfect diamagnet (RQ3).

The cancellation of the YBCO resistance at T = TNL was indicated as a relevant aspect by a third of the sample (RQ3). The explicit connection of the electrical and magnetic properties of a superconductor, emerged only in the 10% of students, remained an open knot for the majority (RQ4).

The exploration carried out enabled the recognition of the central role of temperature in the activation of the superconducting state (RQ3), aspect emerged also in the final summary of more than half of the sample, explaining the change to a superconductive state as a phase transition (23/40). This aspect was activated, as well as not fully recognized, even in those who did not have a clear vision of the ordinary phase transitions such as melting and boiling (RQ4). The deepening of the exploration of the superconducting phase transition can be important not only for understanding the Meissner effect, but also for a phenomenological approach to the concept of phase transition.

Given that there were no significant statistical differences in the responses of the two groups of students, these conclusions can refer to the entire sample, since they do not crucially depend on the previous knowledge or on the age. What was mainly different in the two groups was the representation of the magnetic field inside the magnets and the way they stick to the observation outcomes in their sentences.

We stress in conclusion the importance in the experimentations of the active and collaborative learning environment stimulated by the tutorials and the strong motivation created by the challenging phenomenology, confirming the feasibility of the introduction of superconductivity in high school (Viola 2010; Ostermann, Moreira 2010). The results on the characterization of the Meissner effect indicate how to modify the path to affect the knots in the recognition of the phase transition, in the role of the electromagnetic levitation, in the integration into a common framework of electrical and magnetic properties.

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